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LIQUID METAL EFFECT ON EMBRITTLEMENT PHENOMENA WITHIN THE SOLIDIFICATION RANGE

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Summary: Author tries to present the main results of the long cooperation between the Chair of Foundry of TU-VSB in Ostrava and Faculty of Foundry Eng. AGH in Kraków. The mechanism of brittle failure of cast or welded alloys in the solidification range has been studied. It was supposed that this phenomenon is a particular case of the Liquid Metal Embrittlement (LME). This thesis has been proved by experimental study of the mechanical properties of cast steel nearby the solidus temperature. The kind of fracture depends on the deformation rate. When this rate is low enough the diffusion path, formed by the liquid phase enables the continuous growth of subcritical crack. Then the critical length for ultimate failure can be attained. For higher deformation rate the subcritical growth is too slow and the alloy fails by an alternative process, ductile necking down.

Keywords: hot tearing, solidification, liquid metal embrittlement

1. INTRODUCTION

The phenomena of crack formation during solidification of welds and castings were the subject of numerous investigations, both practical and theoretical [e.g. 1-5]. Tests of various types have been performed to estimate the „susceptibility to crack formation", and therefore the obtained results are not comparable, although they can be regarded as a comprehensive database for theoretical considerations and practical applications in industry. One fact should be emphasized here, i.e. that in the experimental part of the research done so far attention has been focussed on the phenomena of crack propagation rather than on their nucleation. In theoretical research the process of crack formation was extensively studied to develop a model of this process and to establish, as far as possible, some criteria of the crack formation. Due to a complex mechanism of the phenomena which are involved in the process of crack nucleation and propagation, very simplified models have been proposed up to now.

In most cases, these models [1,2,3,5,6,7] discuss an effect of various factors on the critical range of solidification temperatures or on the time the alloy remains within this range. The broader is this range, the greater is the probability that the solidifying weld or casting will suffer a failure.

Rappaz [7] proposed a kinetic model of the crack formation, based on a solution of mass balance equation. According to this model, the crack is formed when the pressure of liquid metal in the area between the secondary branches of dendrites drops to a level below the pressure of cavitation. In that case the microporosity, due to local shrinkage of metal and local deformation when this shrinkage is hampered, cannot be compensated by the liquid metal fed from outside. Such conditions of the crack formation are similar to those suggested by Niyama [8] for the formation of shrinkage microcavities. The milestone in the study of cracking was the construction in Chair of Foundry in VSB the device to measure the UTS and plastic properties of steel, nearby the solidus temperature[9]. In cooperation between the Chair of Foundry and Foundry Departent of AGH it was found that above the end of solidification temperature the UTS of alloy is very low and metal is brittle [5,7]. It was confirmed by the observation of fracture. The brittleness appears during solidification, when the solid crystals form the network able to support the stress resulted from the impending of shrinkage. The brittleness

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is obserwed until the liquid films disappears at the temperature of the end of solidification [5,10,11,12]. The temperature range between the formation of solid network and the end of solidification was called Brittleness Temperature Range (BTR). The disappearing of liquid results in sudden transition from brittle to superpastic state. and the nucleation of the britlle fracture is no more possible. The results of the common studies were presented at the conferences in Teheran [13], Tomsk [14], Tel Aviv [15], Arhus [16] and Patras [17] and published in significant international journals like Int. Cast Metals J. [10], Steel Research [18], Theoretical and Applied Fracture Mechanics [12,19], Steel Founder's Res. Journal [20, 21] etc. It has been proved that the brittle cracks can forms only when the solid grains are separated by liquid films, above the brittle-ductile transition temperature (BDTT). This temperature can be easile measured in tensile test. It is lower then solidus, because of segregation of impurities, mainly sulphur. Chojecki and Telejko [5] observed the fractures in about 60 castings and found that the fractured surface is always covered by the phase rich in sulphur.

The aim of presented paper is to explain the mechanism of brittleness influenced by the liquid phase during the solidification process

2. LIQUID METAL EBRITTLEMENT IN SOLIDIFYING ALLOYS

The phenomena of liquid metal embrittlement (LME) is very important for the nuclear installations where theliquid metals are used as a cooling media. It was examined by Glickman [23, 24] A characteristic feature of LME is that the process of failure does not take place immediately as it happens in, e.g., elastic deformation, but is a time-related function. The brittle fracture remains for quite a long time within the range of subcritical growth. The mechanism of failure depends on whether during the deformation process the brittle fracture is able to attain its critical length before the ultimate failure combined with plastic deformation occurs [23,24].

This is shown in Figure 1 with stress-strain curves plotted for an aluminium specimen in the air, in mercury and in liquid Hg-Ga alloy causing embrittlement [23]. LME mechanism was described by Glickman [23]. Under the effect of stress, the chemical potential □ of atoms rises on the crack tip.This causes diffusion of these atoms from the crack front, described by the equation :

$$dn = M.\ \mathrm{grad}\mu\ dt \qquad (1)$$

where M. is the parameter determining the kinetic conditions of diffusion. An important factor is here the diffusivity of a constituent dissolved in the wetting liquid and the parameters of liquid wetting the solid phase. It has been established [23, 24] that the role of a liquid phase is to make a path for quick diffusion of atoms from the crack tip. Its presence can accelerate the crack growth even as much as a few hundred times [23].

The growth rate does not depend on the stress rate.. Hence it follows that the nature of the crack will depend on the kinetic factors. If the deformation rate is too high, the liquid metal will not have enough time to get access to the crack tip; in a like way the path of easy diffusion will be cut off and the development of a brittle fracture will be impeded. In this case the stress will cause plastic deformation. In the case of solidifying metal, adopting the LME mechanism eliminates the theories according to which cracks are formed within the solidification range through development or fusion of voids formed as a result of inadequate feeding. To what extent, however, are cracks formed in alloys within the solidification range due to LME ? No matter what is the mechanism of the crack tip propagation, in the case of LME the liquid must get access to this tip. According to Poisell, the flow rate is :

$$VL = 0.1\ (w/L)\ (\gamma LV/\eta\ ) \qquad (2)$$

where : w, L - crack width and length, respectively, γLV - tension at liquid/solid interface, η - liquid viscosity.

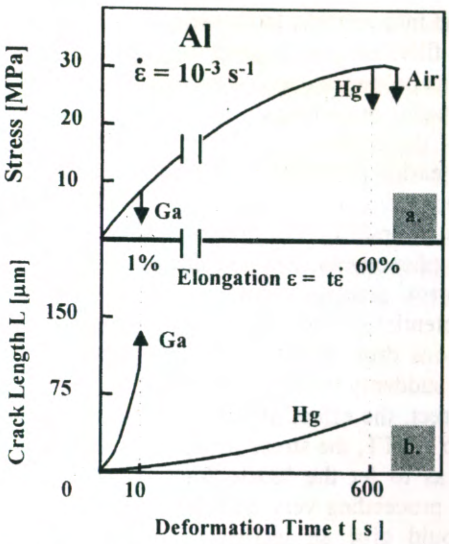

Fig. 1: Stress-strain curve plotted for aluminium sample in the air, in liquid alloy (Hg+3% Ga) and in pure mercury (top part of drawing). Bottom part of drawing - kinetics of fracture plotted for a 1 mm diameter specimen [23]. Arrows denote the instant of failure.

This flow rate impedes the crack growth. In the upper range of BTR, the crack widths are rather large and the viscosity rather low. Therefore VL is always sufficient to fill the crack which is currently forming. This justifies what claim de Sy et al. [25] that in the process of casting or welding solidification cracks always form but in majority of the cases they are filled by an easily flowing metal. In the lower range of embrittlement, the liquid metal fills small isolated areas between the crystals which form subcritical cracks. Acting on the crystal boundaries, the stress breaks them and makes these cracks open. The rate of liquid penetration into the crack opening of a width „w" determined by equation (2) is usually rather high and in the case of typical development of a brittle fracture it reaches 10-2 - 10-1 m/s [23]. A comparison of these values with the rate of the crack length growth dL/dt indicates that the cracks which are nuclei of a brittle fracture are always filled with liquid metal. Until that moment the mechanism of the hot crack formation in alloys and crack formation under the effect of liquid metal is the same, as illustrated by schematic diagram in Figure 2. In LME (Fig. 2b) the volume of the liquid which can penetrate into a crack is unlimited (a vessel of unlimited volume). In the solidifying metal it is restricted to an area enclosed by the dendrite branching (Fig. 2a).

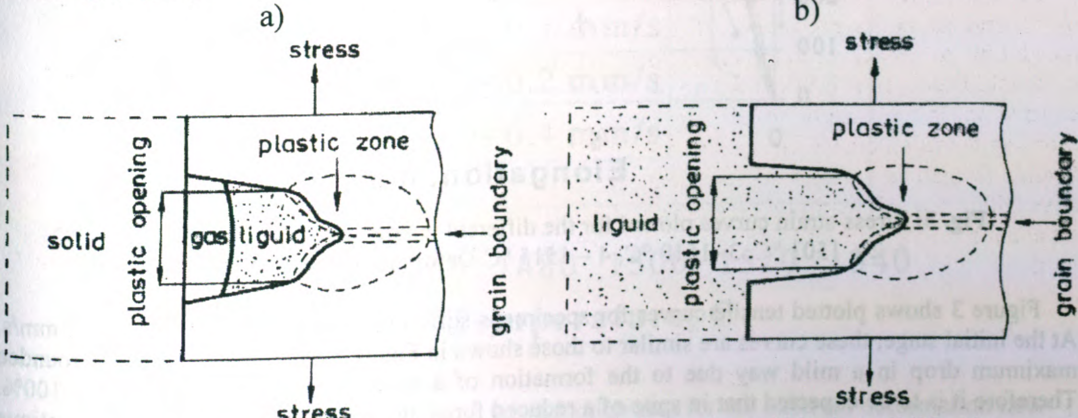

Fig. 2 Schematic diagram of brittle fracture formation : a) - in casting within the solidification range, b) - in typical case of LME [23]

When this liquid is sucked into a crack, the result is formation of a void within the interdendritic space which, if at all, can be filled only with gases evolved from the metal. The void is formed after the crack filled with liquid has propagated and is a consequence and not, as some authors claim, the reason of crack formation in welds or castings.

A characteristic feature of the process of hot crack formation is that the volume of liquid phase decreases with time lapse. In earlier publications [5, 10], the authors drew attention to the fact that if the length of liquid layers separating the crystals is smaller than a preset value, the metal enters the range of very high ductility in spite of the presence of a liquid phase. The authors propose the following explanation of this phenomena. Because the volume of liquid is smaller, it concentrates at the crack tip and within a narrow area around the tip and is no longer the path for an easy diffusion (the gradient of chemical potential suffers a very heavy drop), the more that the increasing liquid viscosity brings a simultaneous drop of diffusivity. The final effect is that the rate of subcritical growth of a brittle fracture is suddenly reduced quite drastically..

If this explanation is correct, the effect of stress should depend on the rate of its increase. At a constant temperature close to BDTT, the stress (or strain) increasing rather slowly should favour the diffusion process so much as to let the brittle fracture reach its critical dimension. When in a specimen the deformation is proceeding very quickly, this deformation is expected to be of a plastic nature. In practice this should give an increasing value of BDTT due to a high rate of the deformation.

3. METHODS ADOPTED IN INVESTIGATION AND RESULTS.

To prove the hypothesis suggested here, from carbon steel with 0.22% C concentration rod specimens of 9 mm diameter were cast. After boring them to Φ8 x 250 mm they were subjected to a tensile test performed on a special testing machine [9]. The specimens were heated under the atmosphere of argon to a preset temperature, close to the temperature of the end of solidification and were next tested for tensile strength at deformation rates of 0.1, 0.2 or 0.4 mm/s.

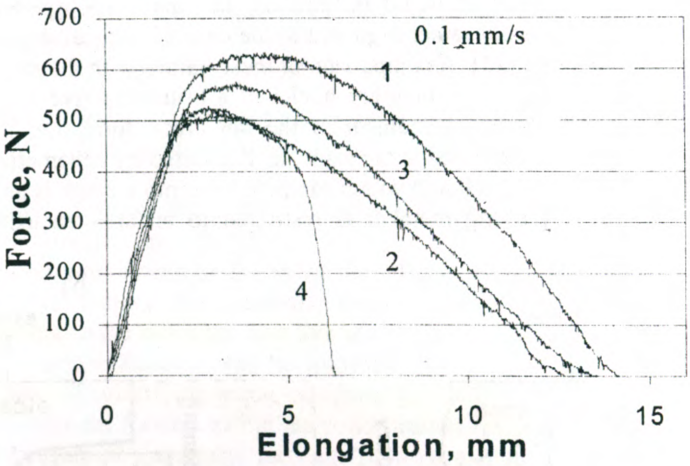

Fig. 3: Stress-strain curves plotted for the different temperature of samples: 1 –1459 °C, 2 – 1501 °C, 3- 1510 °C, 4 – 1515 °C.Deformation rate 0.1 mm/s

Figure 3 shows plotted tensile curves for specimens suffering deformation at a rate of 0.1 mm/s. At the initial stage, these curves are similar to those shown in Figure 1, but having obtained a rounded maximum drop in a mild way due to the formation of a severe necking down, reaching 100%. Therefore it is to be expected that in spite of a reduced force, the stress in the specimen will continue to increase until the plastic failure occurs. In the case of curve 4 this drop is very rapid. With growing deformation, the critical crack size has been reached, finally resulting in brittle fracture. Similar results were obtained with deformation rate equal to 0.4 mm/s, though the transition from brittle to ductile fracture has appeared at a much higher temperature.

The drawing shows, moreover, the changing values of derivatives dF/dl. The change in the nature of fracture is illustrated by rapid drop of the derivative of the tensile curve much more distinct that the drop in force. The derivatives of the tensile curves at lower temperatures are stable unitl the moment when the specimen fails. Figure 4 compares the run of the tensile curves for various deformation rates. It has been noted that an increase in the deformation rate favours the formation of ductile fractures, raising BDTT. This has been confirmed by the results shown in Figures 5 and 6. The drawing also shows the values of the specimen necking down, measured after failure. A very distinct transition from brittle to ductile fracture mechanism is visible. At the transition temperature the specimen necking down is reduced quite obviously.

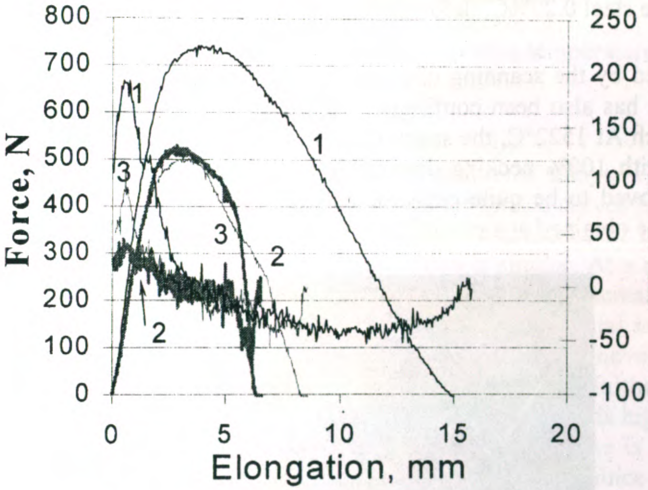

Fig. 4: Stress- strain curves and their derivatives for the different deformation rate: 1- 0.4 mm/s, 1518 °C, 2- 0.2 mm/s, 1515 °C, 3 – 0.1 mm/s, 1516 °C

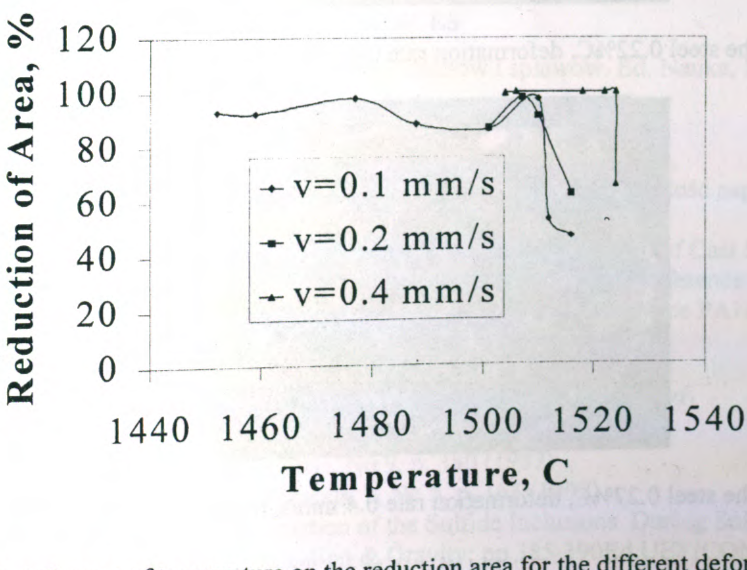

Fig. 5: Influence of temperature on the reduction area for the different deformation rate.

Fig. 6: Fracture of the steel 0.27%C, deformation rate 0.4 mm/s, testing temperature 1522°C, 70.7 x.

It can be confirmed by the scanning obsevation the deformation rate is assumed to have on the transition temperature has also been confirmed. of the cracked surface (Figs 7-9). In this way, the significant effect which At 1522°C, the specimen tested for the tensile strength at a deformation rate of 0.4 mm/s failed with 100% necking down, while at a rate of 0.1 mm/s already at 1515°C the necking down has proved to be quite catastrophic. The results obtained for the tensile rate of 0.2 mm/s are close to those obtained at a rate of 0.1 mm/s.

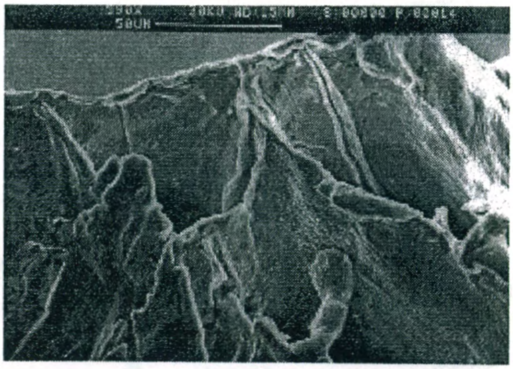

Fig. 7: Fracture of the steel 0.22%C, deformation rate 0.4 mm/s, testing temperature 1516 °C, 598 x.

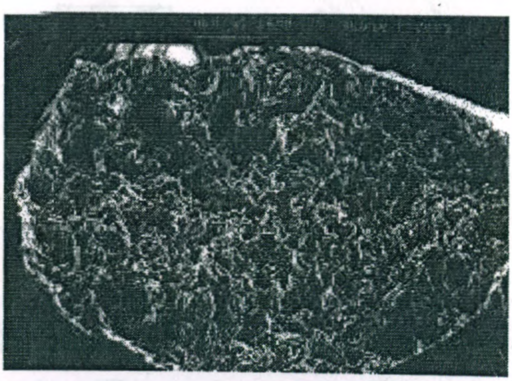

Fig. 8: Fracture of the steel 0.27%C, deformation rate 0.4 mm/s, testing temperature 1524 °C, 70.7 x.

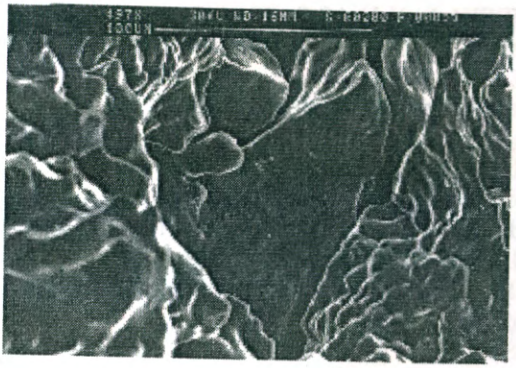

Fig. 9: Fracture of the steel 0.27%C, deformation rate 0.4 mm/s, testing temperature 1524°C, 497 x.

4. RESULTS

The research has proved that the phenomenon of brittle failure of alloys within the range of solidification temperatures is a special case of LME. The run of the tensile curves is very close to that observed in the tensile test madė for aluminium specimens in the presence of Hg-Ga alloys, and hence it can be assumed that the mechanism of this phenomenon is similar. At a temperature above BDTT, the presence of a liquid perfectly wetting the crystals considerably increases the rate of the crack growth in subcritical range. After transition to the ductile state, the initial increase of force is similar, but because the rate of the crack growth is low, the critical size is never reached. Failure occurs with a very severe plastic deformation. It is observed that an increase in the deformation rate causes an increase in ductility, which is manifested in shifting of BDTT towards higher temperatures. So, analysing the mechanism of brittle fracture it becomes clear that its cause is the presence of a liquid phase and not that of the shrinkage voids as was claimed previously, since voids are formed only as a result of the liquid penetrating into the opening crack which is a nucleus of fracture. At the moment when the liquid volume is insufficient, the development of brittle fracture will be hampered in spite of the shrinkage porosities already formed in the alloy.

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